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Enhanced Singular Wave Reactor for Surface Power

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Abstract

The "CANDLE" (Constant Axial shape of Neutron flux, nuclide densities and power shape During Life of Energy producing reactor) also known as singular wave reactor has many significant advantages related to elimination of the need for enrichment. The use of micro-hetero structured fuel, generically called "cer-liq-mesh" will further improve burnup up to 90%. In spite it has typically large dimensions, being heavy to be transported in space, in a single piece, but because it will deliver energy in hundreds MW level for about 100 years per charge using natural Uranium or Thorium as fuel available on the planet's surface, and because it can be assembled locally becomes a very attractive option for self sustainable power cycles. The "cer-liq-mesh" fuel based singular wave reactor is smaller, less than ¼ from the size of "Candle" reactor, and has a very high burnup reducing the fuel cycle drastically. It can be transported by parts, with extremely small probability of over-unity criticality accident and be assembled to run on the surface. This represents a better option for extraterrestrial applications; in spite it requires a more complicated fuel fabrication that pays back in a simplified fuel cycle and minimum waste.

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1. Introduction

The actual terrestrial fuel cycle is mainly customized for pressurized water reactor (PWR) usage but has several major issues. Among the most important is the possible future "uranium peak" similar to the oil peak due to the fact that less than 0.5% of the processed uranium yellow cake is used to produce power, the rest being stored in the used fuel pools for years, to cool-down for reprocessing [1].

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Another very important issue results from the fact that PWRs use enriched fuel, leaving behind large amounts of depleted uranium that can only be used in breeding processes. Breeding produces plutonium, [2] which often encounters criticism based on the slippery grounds of proliferation.

Advanced nuclear energy with its extraordinarily high energy density (both, per unit mass and per unit volume), it produces over seven orders of magnitude less waste than fossil fuels per unit of energy generated. The key is the use of advanced concepts because the terrestrial conventional nuclear energy production and its fuel cycle suffers from depletion of fuel resources [3] even more quickly than fossil power [4]. Integrated breeding and full fuel usage are critical for future success in extraterrestrial surface power. Applying nano-technologies to nuclear reactors could potentially produce the extraordinary performance required.

The key ingredient to any successful outpost implementation is guaranteed by abundant, inexpensive, clean energy. With sufficient energy, all other resources can always be obtained. Energy is also the central resource for cleaning and preserving the environment.

On the surface of the other planets the conditions are very different from the Earth, and the actual fuel cycles developed for Earth will become inappropriate to those conditions, therefore simplified self-sustainable fuel cycles have to be developed and customized for the real conditions. For sure, at the beginning small space reactors will be used on surface too, but novel self-sustainable reactor and fuel cycles will be developed in order to assure local power production. The reactors burning depleted uranium and thorium, with an OTTO fuel cycle and near perfect burning will be the most preferred.

2. Description of the Actual Work

The development of advanced nuclear applications based on micro/ nano-hetero-structures requires intensive use of plutonium and other actinides to complement uranium and to improve performance.

The micro-nano-structured fuel has been developed to eliminate or drastically reduce the actual fuel limitations, including fuel cracking, fission product releases, radioactivity accumulation in fuel, low heat flow, low thermal conductivity, low operating temperatures leading to low efficiency, high waste volume, low burnup factors, and low fuel resources usage. Previous studies (Weber *et al.*, 1956a-b) and experiments have shown that it is possible to engineer micro-nano-structured fuel and achieve improved performance, and even reduce the need for high-hazard chemistry to reprocess the fuel and to partition and separate the fission and transmutation products.

From the theoretical point of view, the new micro-nano-structures can provide control requirements (in order to control a process, they have to be there at the right time, with the right configuration and dimensions, with appropriate sensing and reaction capabilities) applied to nuclear systems with emphasis on the “main actors” in the nuclear reaction that are the moving entities (particles and quanta), including neutrons, fission products, electrons, decay particles, recoils and neutrals (atoms, molecules, up to clusters).

The micro-nano-hetero-structure configuration is made of an assembly of 3 components and interfaces with generic functionality (generator; insulator; absorber) creating an elemental module – specific to the moving entity that can be repeated as many times as necessary.

The “effective length” specific of each moving entity is used to set the correct dimensions of the elemental modules and to design the structure. This design is based on MCMD simulations. These elemental modules may be taken separately or together depending on the abundance of the moving entities and the desired treatment.

A specific list of development elements includes:

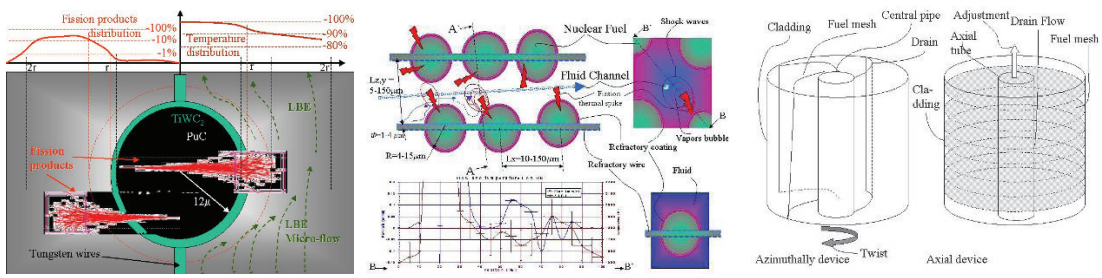
1. The design of the micro-hetero structured fuel “Cer-Liq-Mesh” is based on the fission product’s interactions with the fuel lattice, greatly diminishing radiation damage and maximizing heat transfer, leading to a much more robust materials performance.

2. Nano-cluster-sinter (NCS) structure [5, 6] delivery of isotopic enriched materials with minimal chemical processing exploits the neutron capture reaction kinematics features, synergistically coupled with the nano-cluster properties.

3. The micro-hetero structure and its applications

The Micro-Hetero Nuclear Fuel is also called the "Cer-Liq-Mesh" when it is made of a ceramic fuel structure stabilized on a refractory mesh structure and immersed in a liquid metal, to collect the fission products and smoothly drain them [7].

Figure 1(a) shows a the cross-section of a single Plutonium Carbide (PuC) micro-bead, coated and immersed in a liquid such as Lead-Bismuth Eutectic (LBE) acting as a drain liquid (DL). A particularly important scale is that of the range of the fission products resulting from the nuclear fission. This is due to the fact that these fission products carry the bulk of the energy of the fission reaction and furthermore, that most of the energy deposition per unit path-length and radiation damage are at the end of the range of the fission products [8]. The range of the fission fragments is dependent on their initial kinetic energy, their mass and charge, as well as the composition and density of the material through which the fragments are passing. Taking into account the average kinetic energy shared between the fragments (~170 MeV), and the average values of the other properties mentioned above, the range of the fission fragments is ~ 20-25 μm. Thus the nuclear fuel micro-beads would have a diameter on the order of 20 μm or less and would have center-to-center separations of some 50 μm. As such, the fission fragments would predominantly come to stop outside of the fuel micro-beads [9 – 11], in the liquid metal in which these beads would be suspended (currently proposed to be a lead-bismuth eutectic, although other liquid metals such as sodium-potassium could be used).



(a) **(b)** **(c)**

Figure. 1 (a) A coated plutonium; fuel micro-bead immersed in a drain liquid, with the radial fission products and the plots of their radial distributions for temperature and stopping range, (b) Cross-section and details and temperature distribution of a micro-fluidic channel made of four adjacent beads supported on mesh, and (c) "Cer-Liq-Mesh" fuel pellets with the meat made of compressible structure.

Figure 1(b) shows a lateral section view in a fluidic micro-channel made of adjacent micro-beads chains in the up-left. Underneath, in the lower-left corner are the flow and temperature distributions along the median fluidic channel represented by the blue arrow and the BB' direction. In the lower-right corner is a cross section through the micro-bead similar to that in Figure 1, showing the coating and the refractory wire. In the upper-right corner is a cross section through the micro-fluidic channel in the AA' direction, showing fission energy deposition with its associated thermal spike. It should be noticed that the stopping process takes about 50 ps while the temperature equilibrium is established only after 100 ns or more.

Figure 1(c) shows an example of a compressible "cer-liq-mesh" fuel, similar to a pellet, but made of micro-beads supported on a micro-wire. This has several immediate advantages:

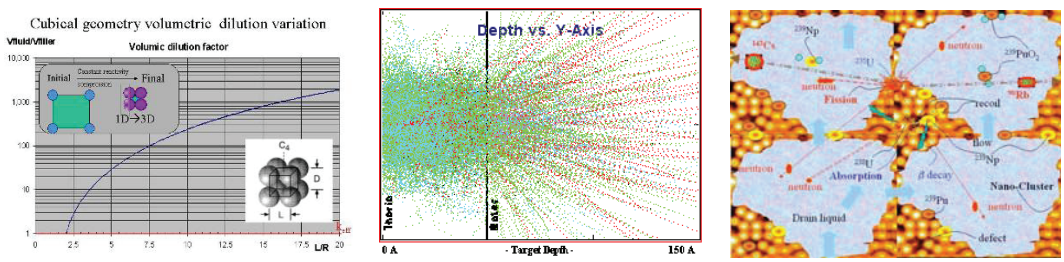
a) The most intense energy deposition and radiation damage would occur outside the ceramic fuel micro-beads (e.g. UO_2), thereby minimizing physical damage to them. The energy deposition would occur in the liquid where there is no physical structure to damage.
b) The fission products, which together typically have a volume several times that of the starting solid fissionable fuel, would come to stop outside of the fuel micro-bead itself and hence, avoid major volume expansion inside the solid fuel beads, thereby minimizing expansion induced cracking of the fuel beads.
c) With the fission fragments coming to a stop in the liquid metal, the fragments could be gradually flushed outside the reactor core by a slow flow, preventing them from poisoning the reactor system by neutron absorption.
d) The approach enables a far greater fractional burning of the nuclear fuel, thereby greatly reducing the radioactive waste.
e) With the use of fuel micro-beads embedded in a liquid metal eutectic, there is less energy deposition in the fuel bead itself (which, has a low thermal conductivity), a smaller thermal conduction path through the fuel before reaching the much higher thermal conductivity eutectic, and a much higher thermal conductivity on average for the reactor system as a whole. This reduces internal temperatures and thermal stress, allowing higher power density.

These structures are compatible with current PWR pellets, thereby giving them enhanced properties. Finally, we note that this fuel structure is capable of handling higher fuel enrichment, higher power densities, higher temperatures, and higher conversion efficiencies.

Figure 2(a) demonstrates the capability of "cer-liq-mesh" fuels to vary its volume in order to compensate for the loss of reactivity due to burn-up. Novel compact reactor designs for continuous fission product separation and ultra high burnup include a variable shape nuclear reactor channel and the means to vary the fuel compression during burnup.

The elimination of the fission products in short time after fission from the nuclear reactor's active zone provides important savings of the fuel and absorption rod mass, reducing the waste mass and complexity.

The actual removal of heat from the reactor core as a whole would still be handled by a secondary working fluid and not by the DL lead-bismuth eutectic. The eutectic would, however, do a much better job of moving the heat resulting from the fission reaction's thermal spike to the secondary working fluid. It also removes the poisoning effect of secondary transformation products and their decay products.



(a) **(b)** **(c)**

Figure 2 (a) The compression of the fuel structure, (b) ^{233}Thorium recoiled out of $^{232}ThO_2$in water, and (c) Nano-clustered enhanced separation of transmutation products.

4. The Nano-Clustered Hetero-structure Direct Transmutation /Breeding Fuel and its applications

The nano-breeding concept would take the above concept one step further by embedding nano-grains of breeding material in a liquid [12]. The relevant scale of interest is even smaller, at least as far as that of the breeding material is concerned. The scale must be small enough so that epithermal or higher energy neutrons that are used to transform the breeding material would provide a sufficient kick to knock most of the now transformed nuclei out of their nano-clusters and into the surrounding liquid, as shown in Figure 2(b), which would then be flushed out of the breeding region. Figure 2(b) analyzed the thoria case, which is very similar to what happens in the depleted urania case.

For any transformed breeding nuclei by a neutron absorption that is not directly ejected from the nano-clusters, the rejection process could be further enhanced using the properties of the nano-clusters and several other effects [5, 6, 13] as Figure 2(c) shows. First, there is the tendency of the atoms of the nano-clusters to arrange themselves in very stable nano-structures [14]. This is further aided by the chemical properties of the transformed nuclei. As a result, "impurity" atoms that are formed as a result of transmutations will tend to be transported out of the interior of the lattice structure to the surface of the nano-clusters, where they can enter the mobile liquid. The energy deposition from the kinetic recoil of the breeding reaction aids the mobility of any trapped transmutation products by displacing them from their lattice positions. The high temperature of the overall system further aids the mobility of the transformed nuclei. Figure 6 shows an example of a depleted urania nano-cluster that produced a transmutation towards ^{239}Pu via ^{239}Np and a fission act on ^{235}U (^{238}U can also fission with fast neutrons). The transmutation products and the elastically recoiled products have the stopping ranges of the order of several nm. The fission product (*i.e.,* ^{143}Cs, ^{90}Rb) stopping range is several tenths of a micron, enabling them to leave the nano-grains.

Additional benefits brought about by the slow, but continuous removal of the newly bred fuel are:

a) The shorter residence time of the breeding product in the reactor core, reducing the presence of secondary breeding products (*i.e*., an undesired second transformation of the desired transmuted product).
b) The ability to, much more easily (and continuously), separate out the newly bred fuel.
c) The ability to fully use the breeding material.
d) The production of both a richer fuel and much less waste.
e) With a proper design, the ability to "continuously" replace the consumed breeding material.

Other minor actinide burning and special interest isotope production (^{238}Pu) may be achieved by engineering a structure that combines the properties of the microstructure with the nano-clustered structure as shown in Figure3b or as shown in Figures 1(c) and 3(a) acting independently. This would enable higher overall process optimization (higher burn-up, higher breeding, better neutron economy, and less waste), providing a new nuclear fuel with reduced negative environmental impact and avoiding the "nuclear fuel peak" by complete usage of fuel reserves.

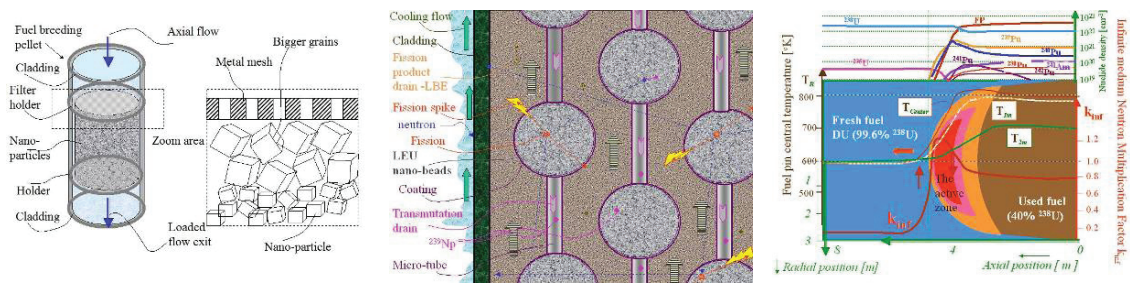


Figure 3. (a) Frit like quasi-nano- clustered fuel pellet, (b) Micro-nano-clustered-hetero structure "nano-clustered cer–liq-mesh" and (c) The CANDLE or moving fuel reactivity wave reactor.

5. Combinations

Due to the similarity of the physics and scales of the above concepts, one could also consider combining them to gain enhanced performance, to have multiple "products," and to meet multiple requirements in a single facility. The main reason for combining applications is the fact that without a breeding program, fission energy simply does not have the needed fuel quantities required for a long-term solution. There are many possible combinations that should be considered. Here we discuss two of these.

A micro-hetero fuel with a nano-clustered transmutation structure - This combination directly separates the fission products and transmutation products, leaving the fuel almost clean and at about the same reactivity [5, 6].

Figure 3(b) shows a section through a nano-clustered-micro-hetero-structure made of nano-frit-like spherules of fuel with an inner liquid that carries the transmutation products connected through a bundle of nano-tubes, all coated in an outer sealing layer, immersed in a drain liquid that removes the fission products. This structure is stabilized and formed into pellets that are inside the cladding whose outer wall is washed by the reactor's cooling liquid.

5.1. "CANDLE" Reactor Type

"CANDLE" (Constant Axial shape of Neutron flux, nuclide densities and power shape During Life of Energy producing reactor) has many significant advantages related to its elimination of the need for enrichment and breeding. It is also a very proliferation-resistant nuclear power source [15]. Figure 3(c) shows a longitudinal section through a "candle" reactor body. Because it uses DU, its dimensions are large (about 8-10 m long and 6-8 m radius). It burns from right to left having the nuclear reaction initiation made with enriched uranium, and immediately after that it burns its DU fuel. In Figure 3(c), the reactor is at 50% of its life, with the active fission zone in the center of the reactor. The lifetime of this system is over 30 years; it has an average burn speed of about ¼ m/year, represented by the red horizontal arrow in center. The abscissa shows the longitudinal dimension "axial position", and the radial position is shown on the left lower vertical axis. On the left ordinate starting from the middle of the axes upwards is shown: the temperature at the center of the fuel pin placed in center of the reactor R=0, the red curve "T_{Center}"; then at R=1m, the brown-yellow curve; than at R=2m, the green curve. It is seen that the temperature has a radial distribution following the shape of the neutron flux intensity shown by the central pattern, where the red area has the largest flux in the active zone. On the right ordinate is shown the criticality of the fuel "k_{inf}" that becomes over-unity only near the center of the active zone. In front of the active zone in the fresh fuel area, the reactivity is 0.2. After the burning zone, the reactivity is 0.8, being sub-critical. On the chart above, sharing the abscissa with the reactor longitudinal section is shown the nuclide concentration as function of axial position at the center of the reactor. This shows the basic mechanism that makes this structure operate like a nuclear reactor. The depleted uranium (DU) – the blue curve - is converted by neutron flux capture into ^{239}Pu – the orange curve. Plutonium and ^{235}U fission and they maintain the reaction in the active zone until the Fission Products (FP) - the brown curve –poisoning weight become sufficient to stop the breeding reaction, making k_{inf} sub-critical. The waste fuel contains several percent of ^{239}Pu and sub-percent amounts of minor-actinides, as shown on the chart. After a few decades the entire fuel is burned and the reaction stops, leaving behind a spent fuel containing about 40% ^{238}U. This process uses about 60% of the extracted natural uranium, making the enrichment and breeding processes followed by Urex or Purex processes unnecessary. Of course, these processes must be applied to the spent fuel to extract uranium, plutonium and the minor actinides. It is important to notice that significant amounts of ^{241}Am, ^{238}Pu, and ^{240}Pu may be obtained after the spent fuel reprocessing, partitioning and separation. This type of transmutation and burning reactor produces a high fuel economy and revolutionizes fuel and waste management. It is also proliferation resistant. The initial delivery contains mainly depleted uranium, and after operation it contains an impressive amount of fission products, making chemical separation difficult.

6. Results and Discussions

The micro-hetero-structure has the main advantage of remaining free of fission products that are drained out by the liquid, while the nano-clustered-structure has enhanced extraction of the transmutation products. Both processes based on the fluid drainage avoid the neutron absorption chain, preventing the formation of heavier isotopes. This process assures a simpler fission products map, and higher purity

transmutation products. Holding the ^{239}Pu longer in the nuclear reactor enables increased fission, neutron absorption and transmutation [13], involving the reactions

$$^{239}Pu\left(n,\gamma\right)^{240}Pu\left(n,\gamma\right)^{241}Pu \xrightarrow{\beta-13.2y} {}^{241}Am\,; \tag{1}$$

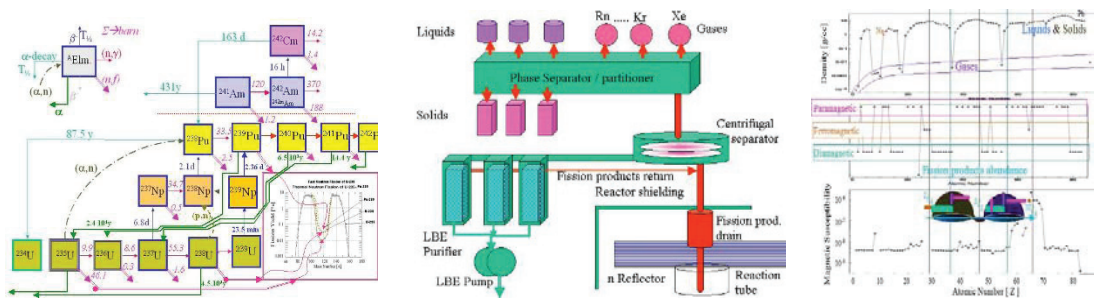
also, shown in part in Figure 4(a).

Having Low Enriched Uranium (LEU) fuel (0.1-0.5%) or residual ^{235}U in the Depleted Uranium (DU) depending on Separative Work optimization for that charge would increase neutron exposure and the probability of neutron absorption becomes important for the following reactions

$$^{235}U\left(n,\gamma\right)^{236}U\left(n,\gamma\right)^{237}U\left[\&\,{}^{238}U(n,2n)^{237}U\right]\xrightarrow{\beta-6.75day} {}^{237}Np\,. \tag{2}$$

These reactions are minimized by the new nano-structure based procedure in order to extract a Super-Grade Plutonium or Uranium.

Figure 4(a) shows the complexity of the nuclear process in actinides near ^{239}Pu. A nucleus-neutron interaction can involve scattering, with or without nuclear excitation or absorption that can induce fission or transmutation leading to a heavier isotope if followed by a multiple gamma or neutron emission or even a different element if a charged particle is emitted. The processes presented in Figure 4a are the main nuclear reactions used for nuclear fuel breeding with emphasis on alpha emitters as ^{238}Pu, ^{241}Pu, ^{241}Am [16].



(a) **(b)** **(c)**

Figure 4. (a) Plutonium zone transmutation diagram, (b) The on-line microchemistry fission product separation system, and (c) Fission products magnetic properties.

The nano-clustered structure shown in Figure 3(a) is used to enhance the separation of the newly created isotopes by transmutation, a process that leaves the structure depleted of higher actinides that may be directly extracted with preferable fuel reprocessing chemical processes.

The micro-hetero-structure shown in Figure 3(b), deals with fission products that have a longer stopping range of about 14 microns in compact urania. There are two main cases of operation of such a structure:

- The static case, in which the fluid is used to enhance the thermal conductivity and the radiation damage robustness, allowing diffusion of the fission products inside following a Brownian path under the influence of buoyancy and,
- The dynamic case, in which the fluid, driven by a pressure gradient, slowly moves through the microstructure, removing the heat produced by the fission products.

In both these cases the pellet is sealed and the fission products do not escape to produce contamination.

The dynamic case involves a continuous circulation of the drain liquid with a speed sufficiently small to avoid hydrodynamic stresses on the fuel beads, but large enough to optimally remove the fission products from the hot zone. This system removes the first group of fission products (^{90}Sr, ^{137}Cs, ^{151}Sm)

and the second group (^{79}Se, ^{126}Sn, ^{93}Zr, ^{99}Tc, ^{135}Cs, ^{107}Pd, ^{129}I), avoiding the undesirable consequences of subsequent neutron absorption, *i.e.*,

$$^{135}Te \xrightarrow{<.5\,min} {}^{135}I \xrightarrow{6.7h} {}^{135}Xe \xrightarrow{9.2h} {}^{135}Cs \xrightarrow{2\times10^{6}\,y} {}^{135}Ba \tag{3}$$

It is known that the yield of ^{135} Te is of about 8% and the cross section of ^{135}I is a factor of 10,000 greater than that of ^{239}Pu, as shown in the lower right of Fig 4a. This simply means that no Pu in a volume of 10 nm^3 around will be burned until the ^{135}Xe is transmuted into ^{136}Xe which has a lower neutron absorption cross section.

The micro-hetero-structure moves the ^{135}I out of the neutron flux and concentrates it in the narrow central drain tube. Only at very high flow rates is the production of ^{136}I minimized. Otherwise it remains in reactor hot zone, but is not shielding the fissile material, in a similar manner to the rim effect being stabilized in drain liquid by a molecular bound. ^{135}I can prevent neutron absorption in nearby liquids or structural materials, at a cost of about 3% of the neutron excess.

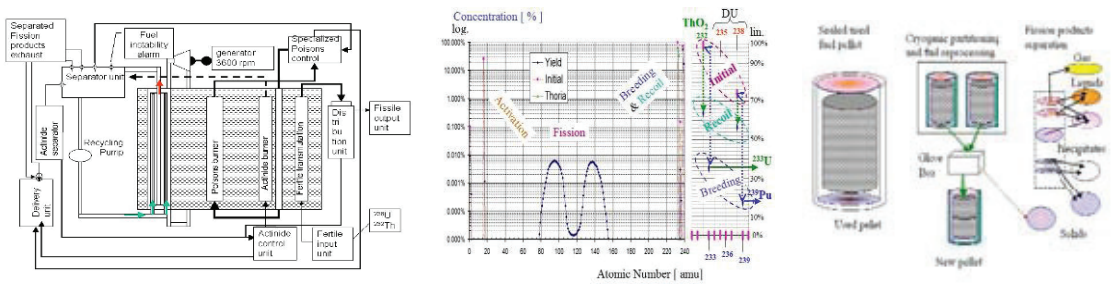
The fission products released into the drain liquid can accumulate on the pellet walls, leading to easy cryogenic separation in the static-fluid encapsulated pellet case. The fission products can also be driven outside the reactor hot zone where they can be separated online as shown in Figure 4(b). The separation process can utilize either centrifugal force exploiting buoyancy or electromagnetic forces to exploit the differences in charge-to-mass ratios as shown in Figure 4(c). The colored rectangles over the dark domes show a possible fission products partitioning.

The upper chart shows the density variation with the element number. The lighter elements are gasses, but at atomic level this property will not manifest directly, except for noble gases that do not interact or dissolve in the drain liquid. For example, until becoming Xe, the buoyancy properties of ^{135}I cannot be utilized because of the Drain Liquid atom-Iodine combination that determines the effective buoyancy.

The middle chart in Figure 4(c) shows the magnetic properties as Ferro-, Para- and Dia-Magnetic, and the lower chart shows the nuclear magnetic dipole moment. The dark grey domes show the fission product density of occurrence distribution, similar to the chart in Figure 4(a), but in an axonometric view to indicate the in-depth distribution due to neutron induced transmutation appears behind the atomic number increasing the complexity of the process.

The micro-hetero structures are novel concepts in reactor fuel management providing continuous separation and extraction of the fission products considered “poisons.” Related dedicated structures can be incorporated into nuclear reactor design, meant to specifically deal with a class of materials, finding similarities with the biology, and living beings.

Figure 5(a) presents a schematic for a nuclear reactor based on dedicated functionalities of the reactor zones. The central zone is dedicated to fission surrounded by dedicated reaction tubes and associated microchemistry devices for burning “poisons” and actinides, and transmutation and fuel breeding.



(a) **(b)** **(c)**

Figure 5. (a) – Novel nuclear reactor fuel management, (b) - Content of the drain fluid for 1:1 Depleted Urania-Thoria nano-clustered breeder, and (c) cryogenic used fuel reprocessing.

The complexity of these processes is much greater because each process including fuel breeding and fuel and minor actinide burning may encounter many fission products. Accelerators and spallation processes can be used to control the neutron balance.

Figure 5(b) gives an example of the numerical simulation of the nano-clustered structure outputs in the drain fluid using a 0.2% or ^{235}U in DU mixed 1:1 with ^{232}Th. The rightmost chart gives a better view of the mass number zone 230-240, barely visible in the original semi-logarithmic chart. The ordinate in linear scale shows the relative breeding concentrations of the products carried out by the drain fluid. The base material, fission products and their transmutation by-products are also visible. These concentrations are orders of magnitude lower than that encountered in spent fuel reprocessing technologies, making this process more attractive.

Another fuel reprocessing option is presented in Figure 5(c) where the cryogenic fuel processing is applied, making the chemical partitioning and separation less hazardous. The process relies on cooling under liquid nitrogen the pellet, unseal it and than warm it up gradually, releasing various fractions in the order of their melting and boiling points, up to the level when the drain liquid is removed from the fuel mesh that remains free of fission products and may be repacked in a new cladding. It is a new re-cladding and partitioning procedure.

7. "CANDLE" Reactor Enhanced Fuel Structures

The advantages of the progressive wave reactor shown in Figure 3(c) can be enhanced by using micro-hetero-structures to produce a "candle" advanced reactor design, similar from the neutronic and fuel handling point of view to pebble bed reactor [17] (because the fuel is moving in order to maintain a steady state in the active zone).

The main purpose of creating a burning wave is to increase fuel burn-up, in order to improve the natural fuel utilization factor and to minimize the need for enrichment [18]. The burn-up is a measure of the fraction of consumed nuclear fuel in atom % and a measure of the extracted specific energy in MW d/kg. Burn-up of 1 atom% produces about 10 MWd/kg.

In order to clearly show [b] the potential advantages of extracting the fission products out of the reactor's active zone and directly separating them by the microchemistry units, a single-group diffusion equation was used [with reference to Figure 3(c) "FP" (fission products) curve] that can be written as

$$\frac{d}{dl}\left(D\frac{d}{dl}\varphi \right)+\nu\Sigma_f\varphi-\Sigma_a\varphi=0 \tag{4}$$

Here, l is the axial position in the reactor; D is the diffusion coefficient; ν is the average number of generated neutrons per fission; Σ is the macroscopic section for fission (f) or absorption and transmutation (a); and ϕ is the neutron flux. The neutron flux will approach zero at the borders of the reactor where l =0 or l =l_{max}.

For a simplified (ignoring radioactive decay and (n, 2n) reactions) transmutation chain of n elements, the burn-up equations are:

$$\frac{\partial N_i}{\partial t}=-N_i\sigma_{a,i}\varphi+N_{i-1}\sigma_{c,i-1}\varphi\,, \tag{5}$$

where $i = m : n$ and for fission products

$$\frac{\partial N_{FP}}{\partial t}=\sum_{i=m}^{n}N_i\sigma_{f,i}\varphi-\eta N_{FP}\sigma_{a,FP}\varphi \tag{6}$$

Here, N_i is the atom number density of element, i; $\sigma_{a,i}$, $\sigma_{f,i}$, and $\sigma_{c,i}$, are the microscopic absorption, fission and capture cross-sections of isotope, i; and FP is the fission product pair.

The macroscopic cross sections are

$$\Sigma_a = N^i \sigma_{a,i}; \tag{7}$$

$$\Sigma_{tr} = N^i \sigma_{tr,i}; \tag{8}$$

$$\nu\Sigma_f = N^i \nu_i \sigma_{f,i}; \tag{9}$$

$$D = \frac{1}{3\Sigma_{tr}} \tag{10}$$

Here, Σ_a and Σ_f, are the macroscopic absorption and fission cross-sections and Σ_{tr} is the macroscopic transport cross section. The burn-up depends on the neutron fluence

$$\psi = \int_0^t \varphi dt \; ; \tag{11}$$

$$l = l_0 + vt \; . \tag{12}$$

So, ψ can also be written as

$$\psi = \frac{1}{v}\int_0^t \varphi dl \; , \tag{13}$$

where v is the displacement speed.

The diffusion equation becomes

$$\frac{d}{dl}\left(D\frac{d}{dl}\varphi \right) + \left[k_\infty - 1 \right] \Sigma_a (\psi) \varphi = 0 \tag{14}$$

The solution can be a solitary burning wave, with an active zone displacement speed, v. The classical solution has a speed in the range of few cm/year and a power density up to 200 MW/m^3.

The effect of the fission-product-removal efficiency, η, in equation (6) is similar to a reduction of the fission product absorption cross section from about 35 barn to obtain the FP_s curve in Figure 6(a) and Figure 3(c) to about 4 barns for the FP_{drain} curve in Figure 6(a). This reduction increases the active zone displacement speed, increases the burn-up factor, and increases the local active zone reactivity.

The corresponding neutron excess can produce higher power densities and improved mixtures of DU-Th and other transmuted isotopes.

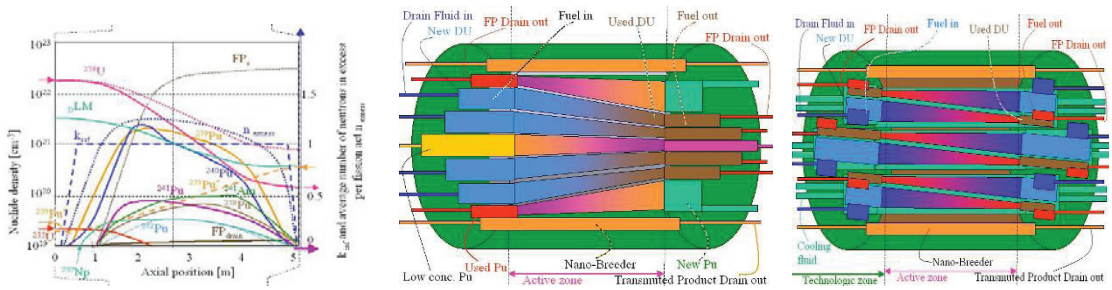
The elastic micro-structure together with a dedicated reaction channel and the use of nano-clustered structures can produce an optimal functionality. One can burn natural uranium mixed with thorium or depleted uranium. One can also concurrently produce by transmutation commercially valuable isotopes needed for power, industrial, and medical applications.

In Figure 6, two versions of nuclear reactor are shown that use variable-geometry micro-hetero-structured fuel in combination with nano-clustered transmutation fuel as the reflector and blanket. Also shown are the longitudinal concentrations of various heavy metals and fission products.

The reactor schematic diagram shown in Figure 6(b) above uses a bi-directional conic-shaped fuel tube geometry.

On exterior is fed with Plutonium based micro-hetero-structure with the role to assure the uniform inside neutron flux and excess of reactivity to assure a deep burn-up of the inner DU fuel. The fresh micro-structured DU with a ^{235}U content as low as 0.2% is fed into the reactor through the ports. By using the micro-structured ^{239}PuC, a constant neutron flux is maintained throughout the reactor zone. This zone coincides with the active zone of the solitary reactivity wave in Figure 3(c). The Pu fuel concentration and a compression adjustment is made in order to perform a near perfect burnup of the DU fuel. The center plot in Figure 6(a) shows the evolution of the nuclide densities in the DU fuel. At the entry point,

the fuel is mostly Uranium. Its concentration decreases as the fuel advances. The decrease in Uranium is compensated by the increase in Plutonium isotopes and in the fission products (FP_s) that at the end dominate the nuclide density for the "candle" or Pebble bed reactors. For the micro-structured fuel, the drain fluid eliminates the fission products, as shown in the FP_{drain} curve, leaving an excess of reactivity of up to 10%. The Plutonium family appears through transmutation, and then disappears as a result of the advanced burn-up with the surplus of reactivity sustained by the Plutonium fuel.



(a) **(b)** **(c)**

Figure 6. Schematic diagram of "Candle" burn micro-hetero structured fuel reactors: tube for DU-Th fuel, where (a) uppermost – conic shaped reactor aided by Pu, (b) –the longitudinal dependence of isotope concentration in DU channel of Figure 6(a) with fuel traveling from left to right, and (c) bi-directional fuel loading reactor using DU-Th only, with transmutation capability.

In Figure 6(c) another case of DU reactor mainly is shown with the fuel traveling in both directions. The charts in Figure 6(b) are only valid for the fuel traveling from left to right. For the fuel moving in the opposite direction, the chart axial axes have to be reversed, because the reactor is symmetrical, and fuel is moving in both directions assuring a very uniform neutron flux, burning zone

8. Conclusions

This type of reactor has to have large dimensions. These dimensions are needed to assure criticality and a good neutron economy. Both are achieved by reducing the lateral surface leakage factor. Using a reflector and a transmutation absorber further minimizes this leakage. A "Candle"-burn type micro-hetero-structure with continuous fission product removal produces a low enriched Uranium product that offers a near perfect burning and simplified fuel reprocessing. It is better than the OTTO Cycle because almost all the actinides are consumed.

The "added complexities" of the micro- and nano- hetero structures provide exceptional burn-up, reducing the waste products almost to their physical limits. Compared with a "candle" reactor burn-up of 40% of the uranium, the enhanced micro-nano hetero structured reactors is capable of improving this limit to 90% uranium burn-up. This burn-up greatly simplifies reprocessing, but adds concerns about the cladding and structural materials integrity under radiation damage, making re-cladding a necessary process. Plutonium used to aid the uniformity of the burning inside the active zone is recovered and can be utilized in subsequent fuels.

The fuel cycle is simplified by minimizing the need for enrichment. Thorium fuel may used as well, due to assisted Plutonium recovered by the nano-clustered fuel.

The continuous separation of fission products to waste increases the leakage risk, but minimizes the potential hazard of the leakage by having minimal fission products accumulation in the fuel.

The fission products are not entirely bad and useless materials; some of them have interesting properties and significant applications. Some of these products can only be stored. These products could be very precious assets in the future. The storage of the purified separated fission products is made easier because the required chemical stability can be assured.

In conclusion, the added Plutonium provided by the micro-hetero fuel eliminates the need for separation and the need for spent fuel storage pools. It reduces to a minimum the waste fission products and simplifies their storage, replacing the geological disposition with storage as a valuable resource.

This new fuel cycle more completely utilizes yellow cake as input for the cer-liq-mesh and nano-clustered fuel production. The reactor burn-up provides fission product separation, minimal fuel reprocessing and useful isotope extraction and stabilization. The hazard exposure is reduced by several orders of magnitude compared with existing fuel cycles. This fuel cycle aiming to completely utilize existing uranium and thorium reserves without enrichment is the most suitable for surface power, making the local fuel cycle doable in the specific conditions of the new planets.

Definitions/Acronyms

"cer-liq-mesh" = ceramic-liquid-mesh fuel made of coated ceramic micro-beads set on a mesh deep in a "drain" liquid, forming the micro-hetero structure of the fuel.

"nano-clustered" fuel = a "frit" filter similar to a fuel formed of a quasi-nano-cluster beads, sinter-washed by a drain liquid.

"CANDLE" (Constant Axial shape of Neutron flux, nuclide densities and power shape During Life of Energy producing reactor)

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